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Estimates of Running Ground Reaction Force Parameters from Motion Analysis

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Running Title: Estimation of running GRF

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Abstract

We compared running mechanics parameters determined from ground reaction force (GRF) measurements with estimated forces obtained from double differentiation of kinematic (K) data from motion analysis in a broad spectrum of running speeds (1.94-5.56 $m \cdot s^{-1}$). Data were collected through a force-instrumented treadmill and compared at different sampling frequencies (900 and 300 Hz for GRF, 300 and 100 Hz for K). Vertical force peak, shape, and impulse were similar between K methods and GRF. Contact time, flight time and vertical stiffness (k_{vert}) obtained from K showed the same trend as GRF with differences <5%, whereas leg stiffness (k_{leg}) was not correctly computed by kinematics. The results revealed that the main vertical GRF parameters can be computed by the double differentiation of the body centre of mass properly calculated by motion analysis. The present model provides an alternative accessible method for determining temporal and kinetic parameters of running without an instrumented treadmill.

Keywords: running mechanics, instrumented treadmill, spring-mass model, gait analysis, kinematics.

Word count: 2101

Introduction

The ground reaction force (GRF) parameters during locomotor activities are extensively used in studies clinically or mechanistically oriented. The forces exerted on the ground are widely used by physiotherapists/orthopaedics and physicians who seek to know the functional responses of surgical or non-invasive interventions[1,2], by neurologists to understand the function of the central nervous system through effector responses on locomotion[3] and by sport scientists analyzing the mechanical predictors of injury and performance[4]. Many attempts have been carried out to comprehend if, and how the running mechanics are related to athletic performance throughout two main strategies: kinematic, kinetic and neuromuscular variables of running mechanics[5,6,7] and the use of descriptors based on spring-mass model[8,9].

Furthermore, from the integrative point of view, the running mechanics have been studied with two approaches: i) a mechanical energy level of the body centre of mass (BCoM), where the increment of the total energy is the work performed by the muscles as proposed by Cavagna and collaborators[10,11] or ii) by using the paradigm of the spring mass model, where the human body is idealized to a point mass at the BCoM supported by a massless spring[12] in order to describe the elastic properties of the runners, as vertical (k_{vert}) and leg (k_{leg}) stiffness. It is worthy of note that the few studies to date that have employed the spring-mass model, in general, have used only stiffness leg and vertical (see Brughelli and Cronin's review[13]) and contact time[14] without a wider look at the bouncing system.

Both these approaches are based on the GRF analysis, notwithstanding, there are limitations in using ground-mounted force platforms due to i) within- and between-subject variability due to difficulty to walk/run at specific and constant speeds[10], ii) stride number limited to plates number and space in the lab and, iii) necessity to introduce constants related to global reference in order to determine the absolute vertical position and horizontal speed[8].

Furthermore, instrumented modern treadmills are very expensive (>100 kUSD[15]), and, especially commercial versions, measure only the vertical forces with acceptable (defined as ≤5%) accuracy[16,17].

On the other hand, motion analysis systems allow collecting a greater stride number. Moreover, in recent years, this technique has been refined with improvements in the estimation of inertial properties of body segments and major accuracy due to an enhanced quality of cameras (resolution > 11 megapixels or 4064x2704; sampling rate > 100 Hz). This approach has been used since the 90's to determine mechanical energy/work[18,19] and recently Morin and co-workers[9,20] developed an interesting and simple method for estimating k_{vert} and k_{leg} starting from kinematics parameters such as contact and flight time. Curiously, the feasibility of motion analysis systems to estimate the running GRF from BCoM is unknown yet. One likely limitation of the procedure could be related to relatively low data sampling (~100 Hz), especially to calculate variables with high-frequency components as rate of force development and vertical impact peak.

The main purpose of this study was to examine the validity of using motion analysis system to estimate selected GRF (e.g., impulse, peak GRF and rate of force development) and spring-mass-based parameters of running. We checked our hypothesis that GRF could be estimated from motion analysis system by addressing three questions: i) may GRF and bouncing system-based parameters be estimated from motion analysis system? ii) What are the effects of sampling frequency on these estimations? And iii) how do these estimates respond at different speeds of locomotion?

Methods

Subject and Protocol

One participant (1.78 m height, 63 kg body mass) skilled with treadmill locomotion ran at incremental speeds: 1.94–5.56 $m \cdot s^{-1}$, with 0.28 $m \cdot s^{-1}$ increments; at each speed data were collected for one minute after the participant reached a steady locomotion and three minutes of rest elapsed between each acquisition. The study was approved by the University Ethics Committee, and the participant signed an informed consent before the experimental test.

Data Acquisition

Kinematics data were collected using an 8-camera Vicon system (6 MX1.3, 2 T20-S, Oxford Metrics, UK) at a sampling rate of 300 Hz. The BCoM position was computed by an 11-segment model[18] based on Dempster inertial parameters of body segment[21]. Marker's position was filtered through a 'zero-lag' second order Butterworth low pass filter with a cut-off frequency detected by a residual analysis on each marker coordinate[21]. A Mercury LT med treadmill (HP Cosmos, Germany) with a 1.5 m long and 0.5 m wide belt, equipped with four tridimensional strain-gauge force traducers[22] was used to collect GRF at 900 Hz. GRF were filtered based on the spectral analysis, which showed peaks of noise frequencies at 39, 47, 110 and 114 Hz that were speed independent. Force traces were filtered through a forward and reverse low-pass, 4th order Butterworth filter with a cut-off frequency of 30 Hz. In both cases, data were down-sampled after the filter. BCoM from GRF was computed by double integration according to Cavagna[23] and integration constants were calculated as described in Saibene and Minetti[24]. All data were analyzed with purposely written Labview programs (v10, National Instruments)

Data Analysis

For each speed, the same number of strides (n=130) was analyzed. BCoM trajectory computed from kinematics was double differentiated to obtain acceleration and multiplied by participant mass to calculate force values. Peak value was calculated from the vertical force trace. Contact time and flight time were measured using a 10 N threshold (when vertical force was above and below 10 N respectively). The same threshold was used to calculate contact and flight time from GRF. For both methods impulse was calculated as the time integral of vertical force and rate of force development was calculated as the slope of vertical force in the interval between 25 and 75 % of peak.

Vertical stiffness (k_{vert}, $kN\cdot m^{-1}$) was calculated as

$$k_{vert} = F_{max}/Dz_{BCoM} \quad [1]$$

where F_{max} is the peak of vertical force (N) and Dz_{BCoM} the vertical displacement of BCoM during stance (m)[25].

Leg stiffness (k_{leg}, $kN\cdot m^{-1}$) was calculated as

$$k_{leg} = \frac{F_{max}}{Dz_{BCoM}+\left[L\left(1-\cos\sin\left(\frac{vt_c}{2L}\right)\right)\right]} \quad [2]$$

where F_{max} is the peak of vertical force (N), Dz_{BCoM} the vertical displacement of BCoM during stance (m), L is leg length (great trochanter height, m), v is progression speed ($m\cdot s^{-1}$), and t_c is contact time (s)[25]: and also as

$$k_{leg} = \frac{F_{max}}{L-\sqrt{L^2-\left(\frac{vt_c-d}{2}\right)^2}+Dz_{BCoM}} \quad [3]$$

where F_{max} is the peak of vertical force (N), L is leg length (great trochanter height, m), v is progression speed ($m\cdot s^{-1}$), t_c is contact time (s), d is the distance of the point of force application translation (assumed to be 0.157 m as described in Morin et al.[26]), and Dz_{BCoM} the vertical displacement of BCoM during stance (m)[26]. The main difference between eq.2 and eq.3 is the point of force application, which is fixed in eq.2, whereas it is translated of d in eq.3[26]. Further analysis of effective spring mass model are presented in Supplementary material.

Statistics

The results were expressed as means ± SD. Normality of the data was confirmed using the Kolmogorov-Smirnov test. When normally distributed, differences among the four methods (GRF 900 and 300Hz; BCoM 300 and 100Hz) were tested for the 14 speeds (1.94-5.56 $m \cdot s^{-1}$) using a One-Way ANOVA for repeated measures. When a significant F-value was found, Bonferroni's post hoc test was used. The non-parametric data were analyzed with a Friedman test using posterior Wilcoxon test as post-hoc. The significance level was set at $\alpha=0.05$. Analyses were performed with SPSS v22 (IBM, USA). We also calculated the percentage difference between the direct biomechanical measure (GRF) and the variable estimates from motion analysis method (F_{peak}, t_c, t_a, Dz_{BCOM}, RFD, Impulse, K_{vert}, K_{leg}, $K_{legMorin}$).

Results

Kinematic methods (at 100 and 300 Hz) resembled vertical force time course during stance, whereas the antero-posterior force, although resembling the double peak pattern, did not match properly (in amplitude and time) peaks values (Figure 1).

The kinematic methods showed a similar trend to that of GRF for the investigated variables at increasing speeds (Figures 2, 3). Overall no significant differences were found between GRF 900 and GRF 300, whereas all the variables were significantly different between GRF (900 and 300 Hz) and kinematic methods ($p<0.01$) and within kinematics (300 vs. 100 Hz, $p<0.01$). When analysing these differences over the whole range of speed quantitatively, contact time was 0.0091±0.0067 s different between GRF and BCoM 300 Hz, 0.0086±0.0059 s between GRF and BCoM 100 Hz, and 0.0052±0.0013 s between kinematic methods (average percentage difference in all speeds lower or equal to 5%). The differences among methods, as a percentage of average value, are not striking. The differences for contact and flight time were lower than 5% of the average values and vertical impulse <1%. The time to vertical peak, Dz_{BCOM} and rate of force development were lower than 10% of the average values.

As for the spring mass model prediction, no significant differences were found within GRF methods. Kinematic methods showed the same trend as GRF for k_{vert} at increasing speeds with significantly different values ($p<0.01$) (Figure 4).

Discussion

Here, we validated the method of double differentiation for determining key mechanical parameters of running by providing a direct comparison against the GRF method, confirming our hypothesis. Specifically, the kinematic method is valid to estimate the parameters directly related to vertical force: peak, shape and impulse.

The duration of contact and flight were similar between methods and it seems more accurate and precise than just one accelerometer[14]. While the present method presented differences in the contact time that did not exceed 5% (<10 ms) in comparison with the GRF method, the accelerometers achieve differences of approximately 30-35% (59-86 ms, at speeds ranging from 12 to 21 $km{\cdot}h^{-1}$)[14]. The convergent validity of flight time estimates using commercial accelerometer is lower indeed achieving errors ranging from 74% (at 12 $km{\cdot}h^{-1}$) to 40% (at 21 $km{\cdot}h^{-1}$)[14]. We found errors for time flight lower than 5%. Likely because the segmentation of the body, instead of one single point where the accelerometer is placed, allows a better estimation of BCoM and, consequently, of vertical force. Also, when using a more refined approach dividing the superior (aerial, t_{ae}) and inferior (contact, t_{ce}) phase of the spring mass[27], these two parameters are well estimated by kinematic methods (Supplementary material).

The principal parameter for describing the spring-mass model is k_{vert}. The kinematics k_{vert} (Figure 4 and also the k_{vert} effective, S1) is speed-dependent, matching patterns shown in the GRF method and literature[25,27]. On the contrary, k_{leg}, a wider used parameter that resembles only the lower limb spring[20,25], computed from kinematic methods does not match GRF pattern. This discrepancy seems to be mainly determined by the vertical BCoM displacement during contact (Figure 2c): in kinematic methods, it is lower at slow speed and higher at faster speed than GRF. As already pointed out[28], the vertical BCoM in running is overestimated. This bias is included in the BCoM calculation with kinematics since the segments are assumed to be rigid and do not account for any visceral/wobbling mass[29]. As shown by Minetti and Belli[30] the visceral mass oscillates with a phase shift compared to the trunk, which determines a smaller BCoM excursion that is detectable by force plates but cannot by kinematics.

The rate of force development, a variable often used in injury prevention[31], is matched by kinematic methods at the speed lower than four $m \cdot s^{-1}$ because the time to peak was overestimated over that speed probably due to its nature of high-frequency. The limb posture at initial contact seems to be linearly related to subsequent loading patterns in stance at low speed ($2.94\ m \cdot s^{-1}$)[32]. Our findings are in line with the similar approach used in dance movements[33].

The sampling frequency effect seems not to be the determinant of the GRF/kinematics differences, when comparing both methods at the same frequency (300 Hz) the parameters are still unequal.

When results are compared within methods, GRF did not show any difference when the signal was downsampled. On the contrary, we found out some differences in kinematics. However, they are always smaller than 5%, much lesser than speed variation. Then, even accounting for a systematic error, the overall trend is well matched also by the low-sampled 100 Hz kinematic methods.

The major limitation of this study regards to the single subject analysis. The aim was to compare different methods, and with the pairwise comparison of a high number of strides, the strength of the estimation (precision and accuracy) can be obtained. Based on the high reproducibility future studies can assess the between subject variability, which could be affected by the assumption of the anthropometric tables used.

In conclusion, when the properly double differentiation technique for the BCoM calculation is applied to running movement, the motion analysis system can be used for the estimation of peak, shape and impulse of vertical force without the need of an instrumented treadmill.

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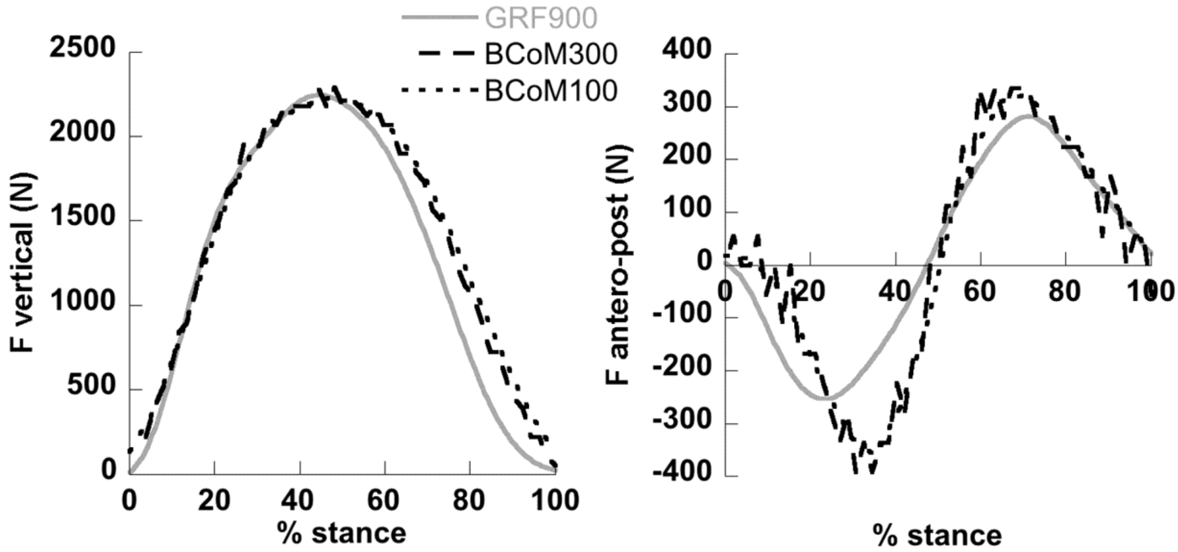

Figure 1 - Example of trace of the time course of vertical (left) and antero-posterior (right) GRF computed by force sensors and kinematics are shown as the percentage of stance phase. GRF300 trace is not shown because it is just one out over three points of GRF900 and is totally covered by the GRF900 line.

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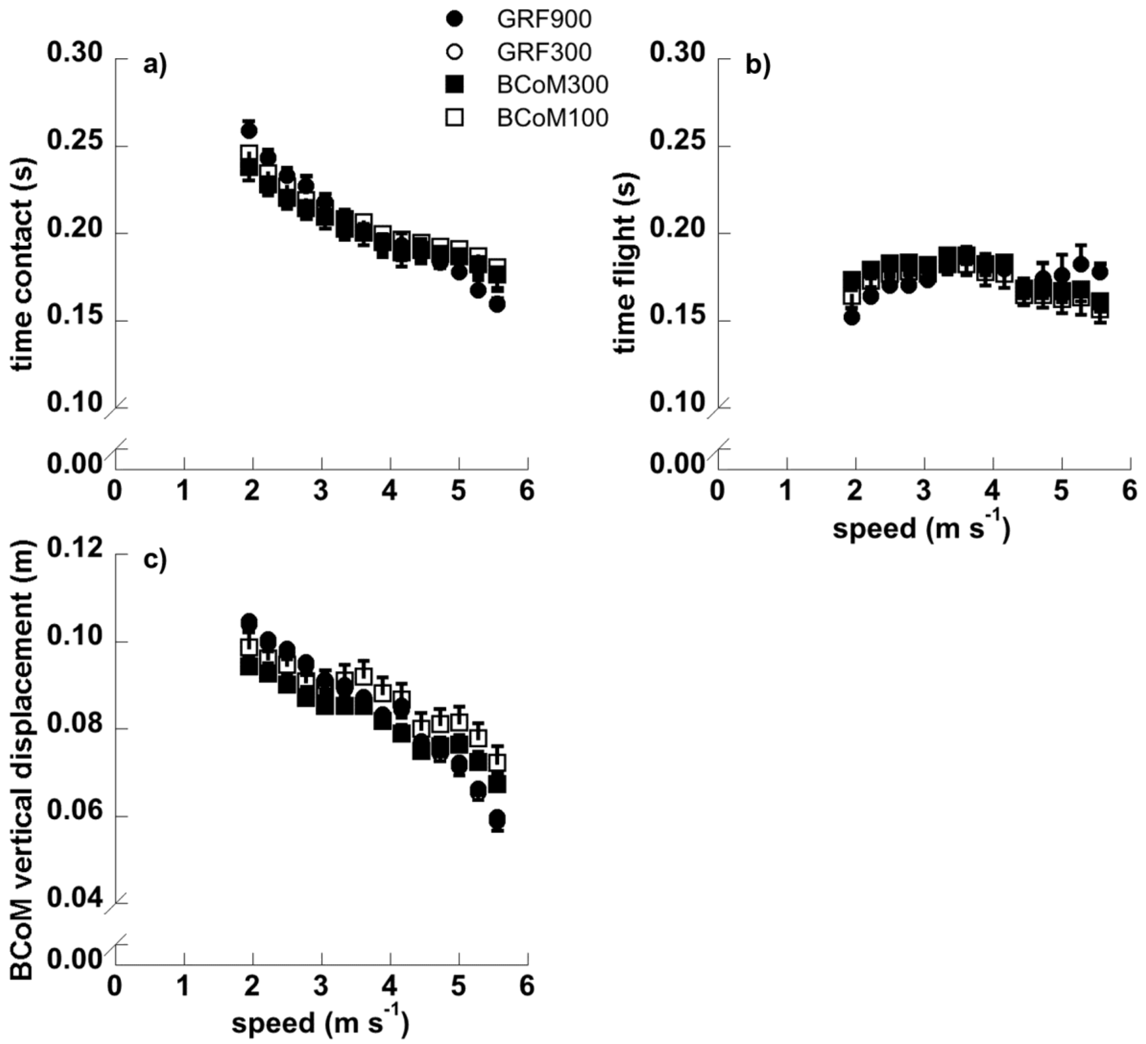

Figure 2 - The mean±SD values of a) contact time (s); b) flight time (s); c) the vertical BCoM displacement (m) computed with different methods as function of running speed are shown. GRF900 and GRF300 showed no significant differences, whereas all the variables were significantly different between GRF and kinematic methods ($p<0.01$) and within kinematics (BCoM300 vs. BCoM100, $p<0.01$). A corresponding figure for effective flight, contact times and BCoM displacement are given in the Supplementary material (Fig. S1).

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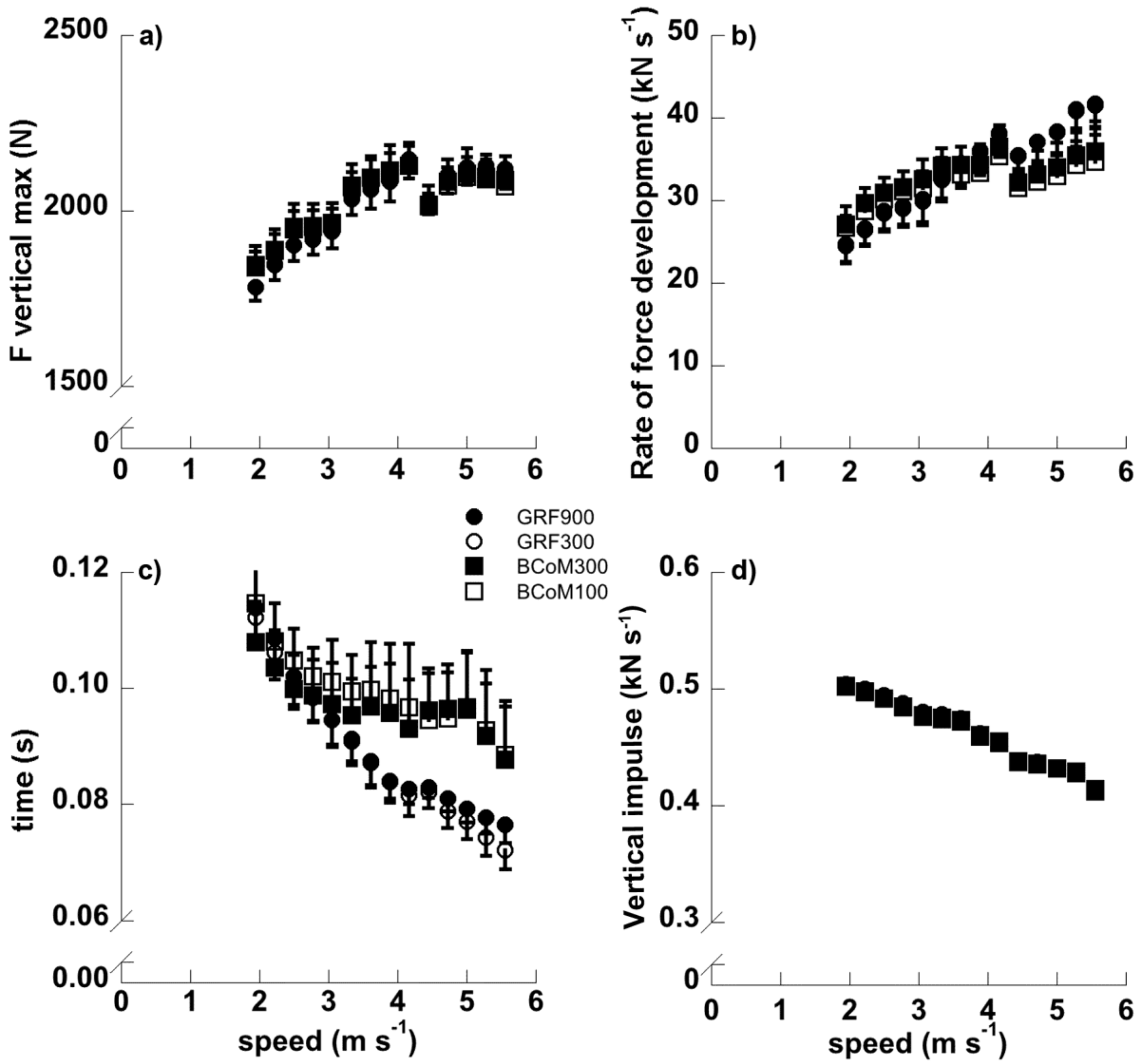

Figure 3 - The mean±SD values of a) the peak vertical force (N); b) the rate of force development (kN·s^{-1}); c) the time to peak (s); d) the vertical impulse (kN·s^{-1}) computed with different methods as a function of running speed are shown. GRF900 and GRF300 showed no significant differences, whereas all the variables were significantly different between GRF and kinematic methods ($p<0.01$) and within kinematics (BCoM300 vs. BCoM100, $p<0.01$).

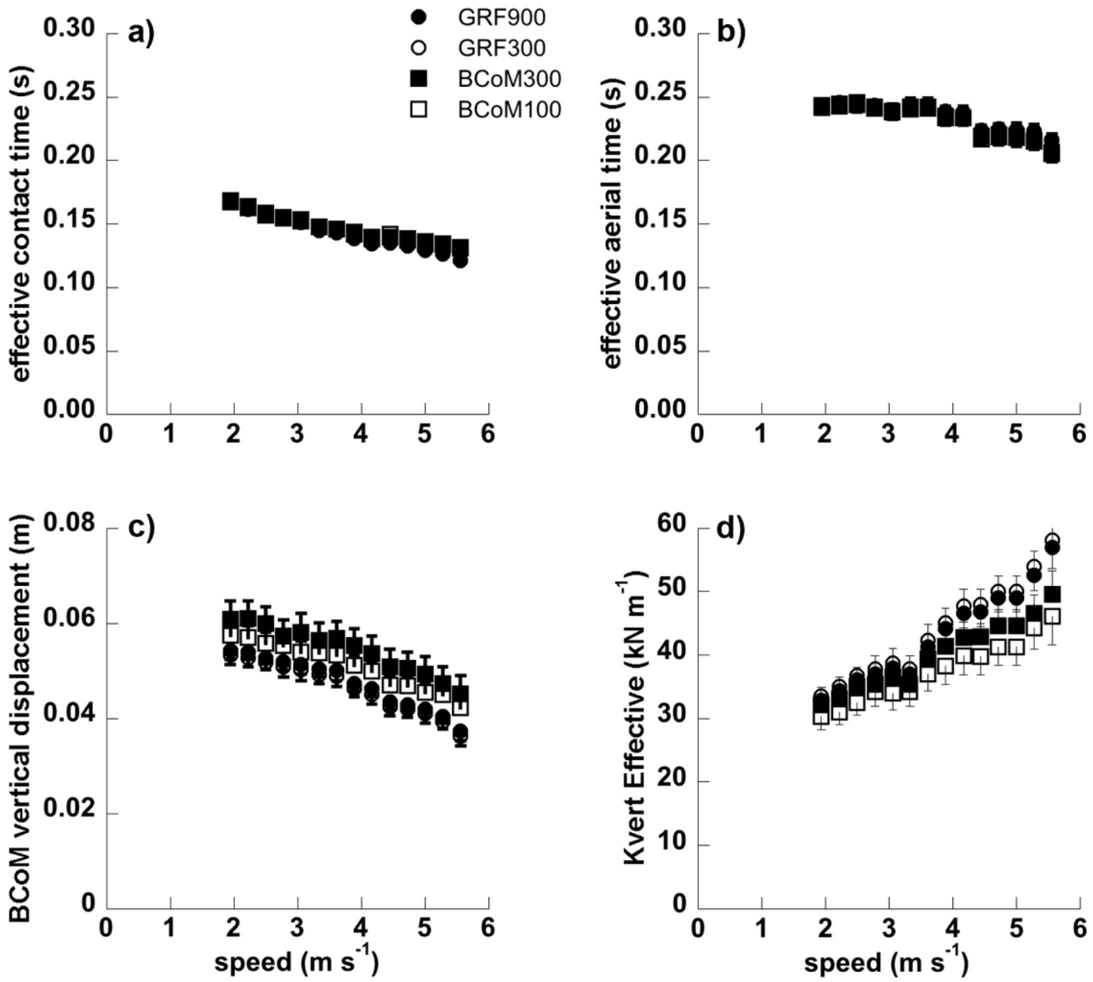

Figure 4 - The mean±SD values of a) the vertical stiffness (kN·m^{-1}); b) leg stiffness (kN·m^{-1}); c) leg stiffness as calculated in Morin et al.[26] (kN·m^{-1}) computed with different methods as a function of running speed are shown. GRF900 and GRF300 showed no significant differences, whereas all the variables were significantly different between GRF and kinematic methods ($p<0.01$) and within kinematics (BCoM300 vs. BCoM100, $p<0.01$).

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SUPPLEMENTAL MATERIAL

Data analysis

Time of effective contact (t_{ce}) is the time where the vertical force is above the body weight; whereas time of effective aerial phases (t_{ae}) is the time where the vertical force is below the body weight[SR1].

The effective vertical stiffness (k_{Evert}, $kN \cdot m^{-1}$) was calculated as: $k_{Evert} = F_{max}/Dz_{EBCoM}$ (Figure S1) where F_{max} is the peak of vertical force (N) and Dz_{EBCoM} the effective vertical displacement of BCoM during stance (m, when vertical force is greater than body weight, Cavagna et al.[SR1]).

The ‘effective’ approach differs from k_{vert} of McMahon and Cheng[SR2] (eq.1) because is able to account the half-period vertical oscillation of the idealized spring-mass model, T_{ce}. This procedure is crucial representing the elastic bouncing, by considering that in many conditions of running (slow speeds[SR1], elderly[SR3], carrying loads[SR4]), the T_{ce} is markedly different from the real contact time.

Results

The times of effective contact and aerial phases did not show any significant difference between GRF (900 vs. 300) methods, and their values were similar between kinematics methods (<1%) without showing a sampling frequencies issue. When analysing the difference between kinematics and GRF, both values at increasing speed were significantly different ($p<0.01$) but the difference was <5% (Figure S1a). Dz_{EBCOM} did not show any difference between GRF methods, whereas the difference between GRF and both kinematics methods was significant ($p<0.01$) with values <10%.

Supplementary References

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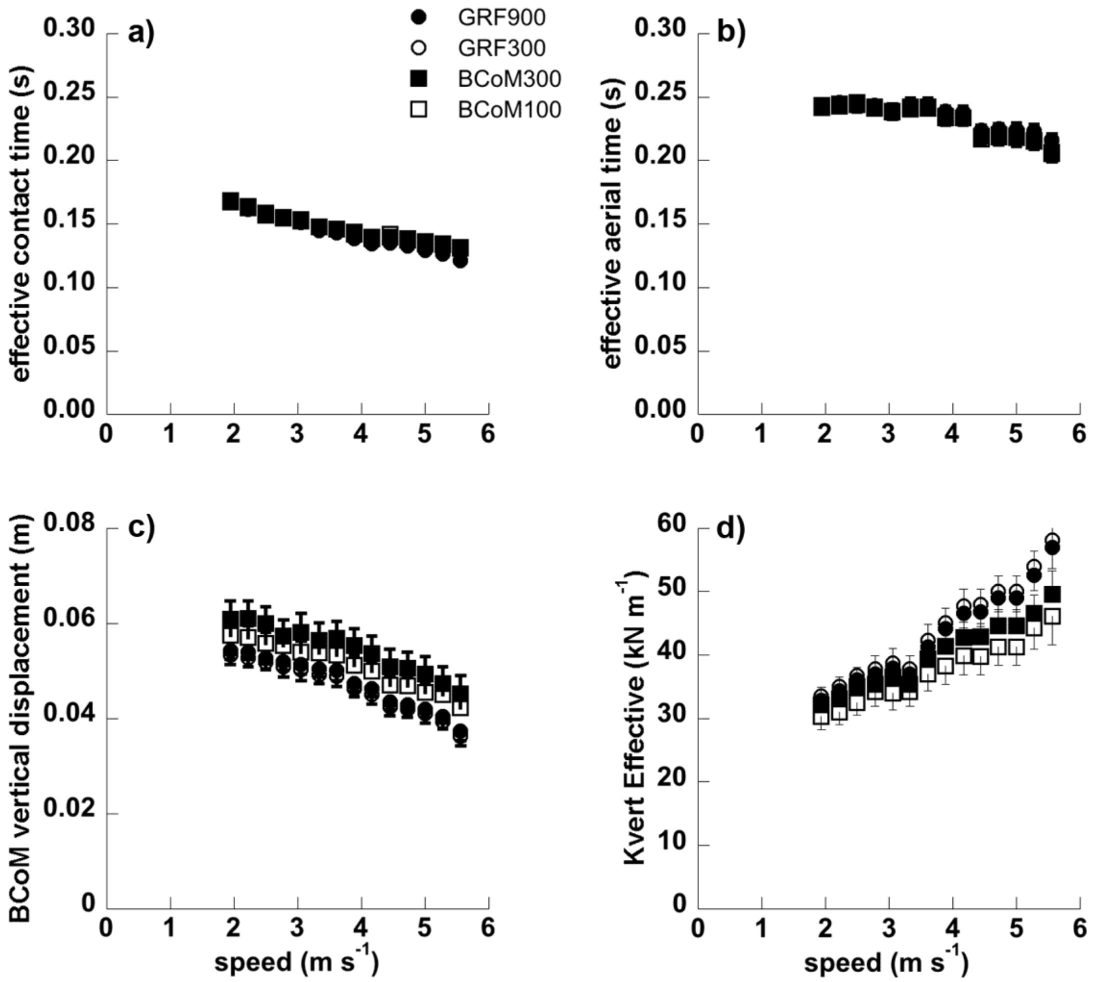

Figure S1 - The mean±SD values of a) effective contact time (s); b) effective aerial time (s); c) the effective vertical BCoM displacement (m); d) the effective vertical stiffness (kN·m^{-1}) computed with different methods as function of running speed are shown.